NASA TECHNICAL NOTE

NASA TN D-2374

NASA TN D-2374

WIND-TUNNEL INVESTIGATION OF BOUNDARY-LAYER CONTROL BY BLOWING ON AN NACA 65_5-424 AIRFOIL TO EFFECT DRAG REDUCTION

by Thomas R. Turner

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1964

WIND-TUNNEL INVESTIGATION OF BOUNDARY-LAYER CONTROL BY BLOWING ON AN NACA 65_5-424 AIRFOIL TO EFFECT DRAG REDUCTION

By Thomas R. Turner

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $0.75

WIND-TUNNEL INVESTIGATION OF BOUNDARY-LAYER CONTROL BY BLOWING ON AN NACA 65_5-424 AIRFOIL TO EFFECT DRAG REDUCTION

By Thomas R. Turner
Langley Research Center

SUMMARY

An investigation has been made to determine the effectiveness of boundary-layer control by blowing in reducing the drag of a two-dimensional airfoil with NACA 65_5-424 sections with the blowing slot located at 0.65 chord. The airfoil was equipped with a 0.35-chord blowing flap. Momentum coefficients ranged from 0 to 0.0233 for the basic airfoil (flap undeflected) and from 0 to 0.0501 with flap deflected. The flap was deflected from 0° to 30°. The Reynolds number for the investigation was 2.96×10^{6}.

Results of the investigation showed that at low lift and momentum coefficients the drag is slightly reduced by blowing and at higher lift coefficients it is greatly reduced by blowing. A blowing momentum coefficient of 0.0107 caused the maximum lift-drag ratio to increase from approximately 20 to 35. These drag reductions are of the same order of magnitude as those for a suction slot at the same location. The increase in maximum section lift coefficients for the basic wing was as great or greater than that for the wing with a suction slot at the same chordwise station. A maximum section lift coefficient of 4.0 was obtained with a flap deflection of 30° and a momentum coefficient of 0.05.

INTRODUCTION

The reduction in induced drag which accompanies an increase in aspect ratio is highly desirable for improved aerodynamic efficiency. However, the potential increases in aerodynamic efficiency (lift-drag ratio) that exist with increased aspect ratio have not been realized because of the high profile drag of the thick inboard wing sections required to achieve acceptable wing weight. Thus, increases in aspect ratio above certain values cause increases in the profile drag which are greater than the decrease in induced drag. This condition has resulted in aspect ratios of 10 to 12 as being approximately optimum for long-range aircraft. If the drag of the thick inboard sections could be reduced by boundary-layer control, by either suction or blowing, advantage could be taken of the potentially higher lift-drag ratios of the higher aspect-ratio wings.

The results of investigations reported in references 1 to 5 indicate that boundary-layer control by suction is an effective method of increasing the maximum lift-drag ratio of NACA 6-series airfoils with thicknesses ranging from 12 to 40 percent chord. Reference 5 indicates that the maximum lift-drag ratio for a hypothetical transport aircraft can be increased approximately 20 percent by the application of suction boundary-layer control.

The separation of the boundary layer over the aft part of an airfoil can be delayed also by adding energy to the boundary layer by blowing high-pressure air streamwise from a narrow slot in the airfoil. This blowing system of boundary-layer control assumes new interest with present-day jet engines capable of supplying large quantities of compressed air.

The purpose of the present investigation is to determine the extent to which the drag of a thick airfoil can be reduced by blowing boundary-layer control and to compare slot suction and blowing as a means of reducing the drag of the same airfoil section. An NACA 65_5-424 airfoil section with the blowing slot at 0.65 chord was used in this investigation. Data were also obtained with a 0.35-chord blowing flap deflected up to 30°. This same airfoil section has been investigated with a suction slot at 0.65 chord with and without a double slotted flap (ref. 4).

SYMBOLS

c_l	section lift coefficient, $\frac{l}{q_\infty S}$
c_d	section profile-drag coefficient, $\frac{d}{q_\infty S}$
c_m	section pitching-moment coefficient, $\frac{m}{q_\infty Sc}$
q_∞	free-stream dynamic pressure, lb/sq ft
V_∞	free-stream velocity, ft/sec
C_μ	momentum coefficient, $\frac{T}{q_\infty S}$
l	section lift, lb
d	section drag, lb
m	section pitching moment, ft-lb

N_{Re}	Reynolds number, based on c
c	airfoil chord, ft
α	angle of attack, deg
δ_f	flap deflection, deg
α_δ	plain-flap effectiveness parameter
S	airfoil area, sq ft
T	static thrust measured with flap off and air exiting parallel to tunnel center line, lb
p	free-stream static pressure, lb/sq ft
p_t	free-stream total pressure, lb/sq ft
$p_{t,p}$	total pressure in plenum chamber, lb/sq ft
T_p	temperature in plenum chamber, $^\circ R$
T_t	free-stream stagnation temperature, $^\circ R$
Q	quantity of air removed through suction slot, cu ft/sec
C_Q	flow coefficient, $\frac{Q}{V_\infty S}$
C_p	pressure coefficient, $\frac{p_t - p_{t,p}}{q_\infty}$
c_p	specific heat at constant pressure
$C_{P,s}$	suction power drag coefficient, $C_Q C_p$
$C_{P,b}$	blowing power drag coefficient, $\frac{C_\mu}{V_J V_\infty} \frac{\gamma}{\gamma - 1} RT_t g\left[\left(\frac{p_{t,p}}{p_t}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$
V_J	blowing slot exit velocity, $\sqrt{\frac{2\gamma}{\gamma - 1} RT_p g\left[1 - \left(\frac{p}{p_{t,p}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$, ft/sec

h	enthalpy
w	mass flow, slugs/sec
R	gas constant, 53.35 ft-lb/lb/$^{\circ}$R
γ	ratio of specific heats, 1.4 for air
g	gravitational acceleration, ft/sec^2

Subscripts:

max	maximum
min	minimum
meas	measured
1,2	reference stations

APPARATUS AND TESTS

The investigation of boundary-layer control by blowing on a two-dimensional airfoil was made in the Langley 300-MPH 7- by 10-foot tunnel. The 2-foot-chord model spanned the 7-foot height of the tunnel test section with the exception of 1/16-inch gaps at either end to allow for movement of the balance system. Mounts went through the tunnel floor and ceiling and were attached to the balance frame. End plates 1/32 inch thick extending approximately 3/4 inch from the wing contour and covering the forward 0.8 chord were attached to both ends of the airfoil. These plates were to insure that leakage around the wing mounts from outside the tunnel could not flow spanwise on the airfoil. The drag of these plates was not subtracted from the airfoil measured drag.

Compressed air for boundary-layer control was brought onto the balance frame through a long $1\frac{1}{2}$-inch-diameter steel pipe that acts as a weak spring (ref. 6). The tares or interactions introduced by this method are negligible.

A drawing of the NACA 65_5-424 airfoil with ordinates is shown in figure 1 and a photograph of the model is presented as figure 2. The model was made of mahogany except that the blowing slot lips and airfoil trailing edge were made of aluminum. The 0.00083-chord, 0.020-inch-gap blowing slot was located at the 0.65-chord station. The 0.35-chord flap was designed to give a minimum change in airfoil contour with the flap undeflected and to take advantage of the blowing slot with the flap deflected.

The tests were made at a dynamic pressure of 54.89 pounds per square foot corresponding to a Reynolds number of 2.96×10^6, except for some tests of the basic airfoil in which Reynolds number was varied. The angle-of-attack range extended from -10° to the stall for most conditions.

CORRECTIONS

The following corrections (ref. 7) have been applied to the data:

$$c_l = c_{l,meas}\left(0.9836 - 0.1037c_{d,meas}\right)$$

$$c_d = c_{d,meas}\left(0.9878 - 0.1037c_{d,meas}\right)$$

$$c_m = \left(0.9920 - 0.1037c_{d,meas}\right)c_{m,meas} + 0.0021c_{l,meas}$$

$$\alpha = \alpha_{meas} + 0.0763\left(c_{l,meas} + 4c_{m,meas}\right)$$

$$q_\infty = q_{\infty,meas} + 0.1037c_{d,meas}$$

RESULTS AND DISCUSSION

This investigation was made at a Reynolds number of 2.96×10^6 primarily; however, the airfoil without blowing boundary-layer control and with the flap undeflected was investigated at lower Reynolds numbers. The maximum lift coefficient decreased with an increase in Reynolds number for the range of the investigation; likewise the minimum drag coefficient had a tendency to decrease with an increase in Reynolds number (fig. 3). The lift-curve slope for the smooth airfoil at a Reynolds number of 2.96×10^6 was 0.107 per degree, practically the theoretical lift-curve slope $\left(\frac{(2\pi)}{57.3}\right)$; it was also in agreement with reference 4.

Transition was fixed at the 0.05-chord position on both upper and lower surfaces by a 1/8-inch band of very sparsely spread No. 60 carborundum grains. The effect of this fixed transition is shown in figure 4. The fixed transition decreased the lift-curve slope, increased the drag, and shifted the lift center forward. The variation of $c_{d,min}$ with Reynolds number for this investigation and $c_{d,min}$ with and without roughness at a Reynolds number of 6×10^6 from reference 4 is shown in figure 5. For the present investigation $c_{d,min}$ appears to be a little high as compared with the value at a Reynolds number of 6×10^6 from reference 4. However, the variation of $c_{d,min}$ with Reynolds number is in agreement with the turbulent skin-friction curve $2C_f$ (ref. 8). The skin friction of the small end plates on the airfoil and the leakage around the wing to the balance mounts contributed a small increment of drag which was included in the airfoil drag. The finish of the mahogany airfoil for this investigation, even in the smooth condition, was probably rough enough to eliminate any large extent of laminar flow on the airfoil; whereas, the airfoil of reference 4 apparently had considerable laminar flow.

The incremental drag values resulting from blowing from the boundary-layer control slot should be approximately correct even though the drag of the basic airfoil (flap undeflected) is high.

The aerodynamic characteristics of the basic airfoil for several values of C_μ are presented in figure 6. In general, the lift-curve slope and maximum lift increased with an increase in C_μ. The aerodynamic center shifted rearward as C_μ was increased. The measured minimum drag decreased by an amount approximately equal to the applied momentum coefficient. However, at moderate and high lift coefficients the drag reduction was considerably greater than the applied momentum coefficient. This is more clearly shown in figure 6(concluded) where the drag coefficient $c_d + C_\mu$ is plotted as a function of c_l. The maximum lift-drag ratio increased from approximately 20 for $C_\mu = 0$ to approximately 35 for $C_\mu = 0.0107$.

The aerodynamic characteristics of the airfoil with the flap deflected as much as 30° are presented in figure 7 for several values of C_μ. A maximum lift of 4.0 was obtained for a flap deflection of 30° and $C_\mu = 0.0501$; however, it is expected that at higher flap deflections higher maximum lift coefficients would have been obtained.

Some of the data are summarized in figures 8 to 12. The incremental lift coefficient Δc_l for the deflected flap for several C_μ values is presented in figure 8 along with the theoretical curve (ref. 9). A value of C_μ of approximately 0.0175 was required to keep the flow attached to obtain the theoretical lift increment for the flap deflected 30°, the highest deflection investigated. It is obvious that the largest C_μ value (0.05) of the investigation would have been sufficient to obtain the theoretical lift increment for considerably larger flap deflections. A summary of the maximum lift coefficients obtained for the various configurations is presented in figure 9.

The power required for a given drag reduction appears to be a satisfactory way of comparing the relative merits of suction and blowing boundary-layer control. The suction boundary-layer control blower power is (ref. 10)

$$\text{Blower power} = C_Q C_P \left(q_\infty S V_\infty\right)$$

and the suction power drag coefficient is

$$c_{P,s} = \frac{\text{Blower power}}{q_\infty S V_\infty} = C_Q C_P$$

The blowing boundary-layer power coefficient is derived as follows:

$$\text{Blower power} = \left(h_2 - h_1\right)w = c_pT_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]w$$

and by definition

$$C_\mu = \frac{T}{q_\infty S}$$

where T is static thrust and for a subsonic jet $T = wV_J$. Therefore, the blower power is

$$\text{Blower power} = c_pT_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\frac{C_\mu q_\infty S}{V_J}$$

and the blowing power drag coefficient is

$$C_{P,b} = c_pT_t\left[\left(\frac{p_{t,p}}{p_t}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\frac{C_\mu}{V_JV_\infty} = \frac{\gamma}{\gamma - 1}\,RT_tg\left[\left(\frac{p_{t,p}}{p_t}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\frac{C_\mu}{V_JV_\infty}$$

The change in drag coefficient $\Delta\left(c_d + C_{P,b}\right)$ or $\Delta\left(c_d + C_{P,s}\right)$ with boundary-layer-control power drág coefficient $C_{P,b}$ (present investigation) or $C_{P,s}$ (ref. 4) for several lift coefficients is shown in figure 10. Blowing gives the larger reduction in drag at $c_l = 0.4$; however, at $c_l = 0.6$ and 0.8 at low power coefficients, suction gives the larger drag reductions.

The variation of maximum lift-drag ratio $\left(\frac{c_l}{c_d + C_\mu}\right)_{max}$ with C_μ for several flap deflections is presented in figure 11. The maximum lift-drag ratio for the basic airfoil occurred at a value of C_μ of approximately 0.01. Small flap deflections gave further small increases in $\left(\frac{c_l}{c_d + C_\mu}\right)_{max}$.

A comparison of $c_{l,max}$ as a function of $C_{P,b}$ or $C_{P,s}$ for the airfoil with the blowing slot and for the airfoil with a suction slot at the same chordwise station and a double slotted flap (ref. 4) is shown in figure 12. For the basic airfoil, blowing and suction have about the same effectiveness. The double slotted flap with no suction is more effective than the blowing flap with no blowing as would be expected; however, as boundary-layer-control power is increased, $c_{l,max}$ for the blowing flap increases faster so that above a $C_{P,b}$ or $C_{P,s}$ value of approximately 0.10 the blowing flap has the same or higher

$c_{l,max}$. The value of $c_{l,max}$ for the blowing flap would be still higher if the flap deflection was increased to the 60° to 75° range.

Since the data indicate that the drag reduction due to blowing is of the same order of magnitude as that from suction on the same airfoil, the analysis presented in reference 5 should be applicable to the blowing condition. This analysis indicates that improvements of the order of 20 percent in l/d can be obtained for an airplane with boundary-layer control.

CONCLUSIONS

A wind-tunnel investigation to determine the effect of boundary-layer control by blowing from a slot at 0.65 chord on the section characteristics of an NACA 65_5-424 airfoil with and without a flap has indicated the following conclusions:

1. The reduction in section drag was approximately the same for slot blowing as for slot suction, with the larger drag reductions at the higher lift coefficients. A blowing momentum coefficient of approximately 0.01 increased the maximum lift-drag ratio approximately 75 percent.

2. The increase in maximum section lift coefficient with boundary-layer-control power coefficient for the basic airfoil (flap undeflected) with the blowing slot is as great or greater than that for a suction slot at the same station.

3. A blowing momentum coefficient of approximately 0.0175 was sufficient to obtain the theoretical lift increment for a flap deflection of 30°.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 3, 1964.

REFERENCES

1. Quinn, John H., Jr.: Tests of the NACA 64_1A212 Airfoil Section With a Slat, a Double Slotted Flap, and Boundary-Layer Control by Suction. NACA TN 1293, 1947.

2. Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on the NACA 65_3-418, a = 1.0 Airfoil Section With a 0.29-Airfoil-Chord Double Slotted Flap. NACA TN 1071, 1946.

3. Quinn, John H., Jr.: Wind-Tunnel Investigation of the NACA 65_4-421 Airfoil Section With a Double Slotted Flap and Boundary-Layer Control by Suction. NACA TN 1395, 1947.

4. Racisz, Stanley F., and Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on NACA 65_5-424 Airfoil With Double Slotted Flap. NACA TN 1631, 1948.

5. Horton, Elmer A., Racisz, Stanley F., and Paradiso, Nicholas J.: Investigation of NACA 64,2-432 and 64,3-440 Airfoil Sections With Boundary-Layer Control and an Analytical Study of Their Possible Applications. NACA TN 2405, 1951.

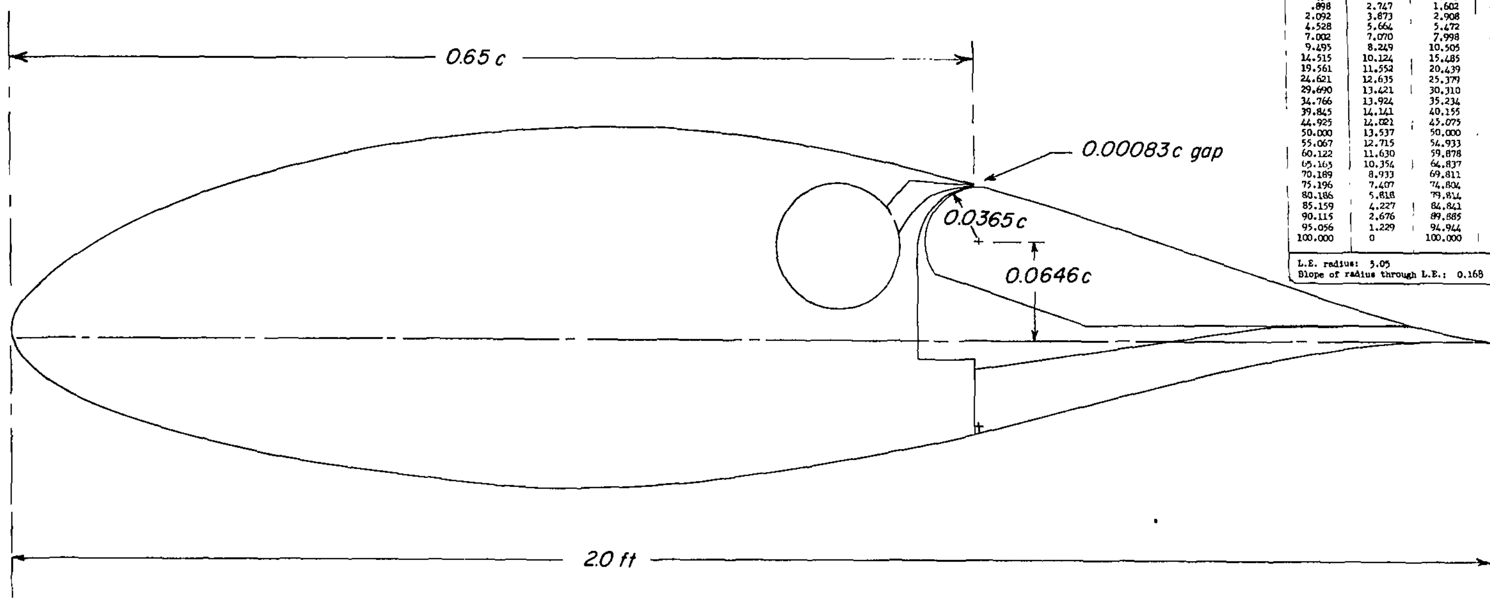
6. Lockwood, Vernard E., Turner, Thomas R., and Riebe, John M.: Wind-Tunnel Investigation of Jet-Augmented Flaps on a Rectangular Wing to High Momentum Coefficients. NACA TN 3865, 1956.

7. Allen, H. Julian, and Vincenti, Walter G.: Wall Interference in a Two-Dimensional-Flow Wind Tunnel, With Consideration of the Effect of Compressibility. NACA Rep. 782, 1944. (Supersedes NACA WR A-63.)

8. Abbott, Ira H., and Von Doenhoff, Albert E.: Theory of Wing Sections. Dover Pub., Inc., 1959.

9. Lowry, John G., and Polhamus, Edward C.: A Method for Predicting Lift Increments Due to Flap Deflection at Low Angles of Attack in Incompressible Flow. NACA TN 3911, 1957.

10. Braslow, Albert L., Burrows, Dale L., Tetervin, Neal, and Visconti, Fioravante: Experimental and Theoretical Studies of Area Suction for the Control of the Laminar Boundary Layer on an NACA 64A010 Airfoil. NACA Rep. 1025, 1951. (Supersedes NACA TN 1905 by Burrows, Braslow, and Tetervin and NACA TN 2112 by Braslow and Visconti.)



NACA 65_5-424 AIRFOIL SECTION

[Stations and ordinates in percent chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.218	1.771	.782	-1.571
.437	2.156	1.063	-1.876
.898	2.747	1.602	-2.319
2.092	3.873	2.908	-3.129
4.528	5.664	5.472	-4.400
7.002	7.070	7.998	-5.374
9.495	8.249	10.505	-6.181
14.515	10.124	15.485	-7.432
19.561	11.552	20.439	-8.368
24.621	12.635	25.379	-9.055
29.690	13.421	30.310	-9.533
34.766	13.924	35.234	-9.804
39.845	14.141	40.155	-9.857
44.925	14.021	45.075	-9.641
50.000	13.537	50.000	-9.125
55.067	12.715	54.933	-8.335
60.122	11.630	59.878	-7.346
65.165	10.354	64.837	-6.234
70.189	8.933	69.811	-5.045
75.196	7.407	74.804	-3.827
80.186	5.818	79.814	-2.634
85.159	4.227	84.841	-1.535
90.115	2.676	89.885	-.608
95.056	1.229	94.944	.035
100.000	0	100.000	0

L.E. radius: 3.05
Slope of radius through L.E.: 0.168

Figure 1.- Profile of the NACA 65_5-424 airfoil section with blowing slot.

Figure 2.- Model installed in tunnel. L-61-6100

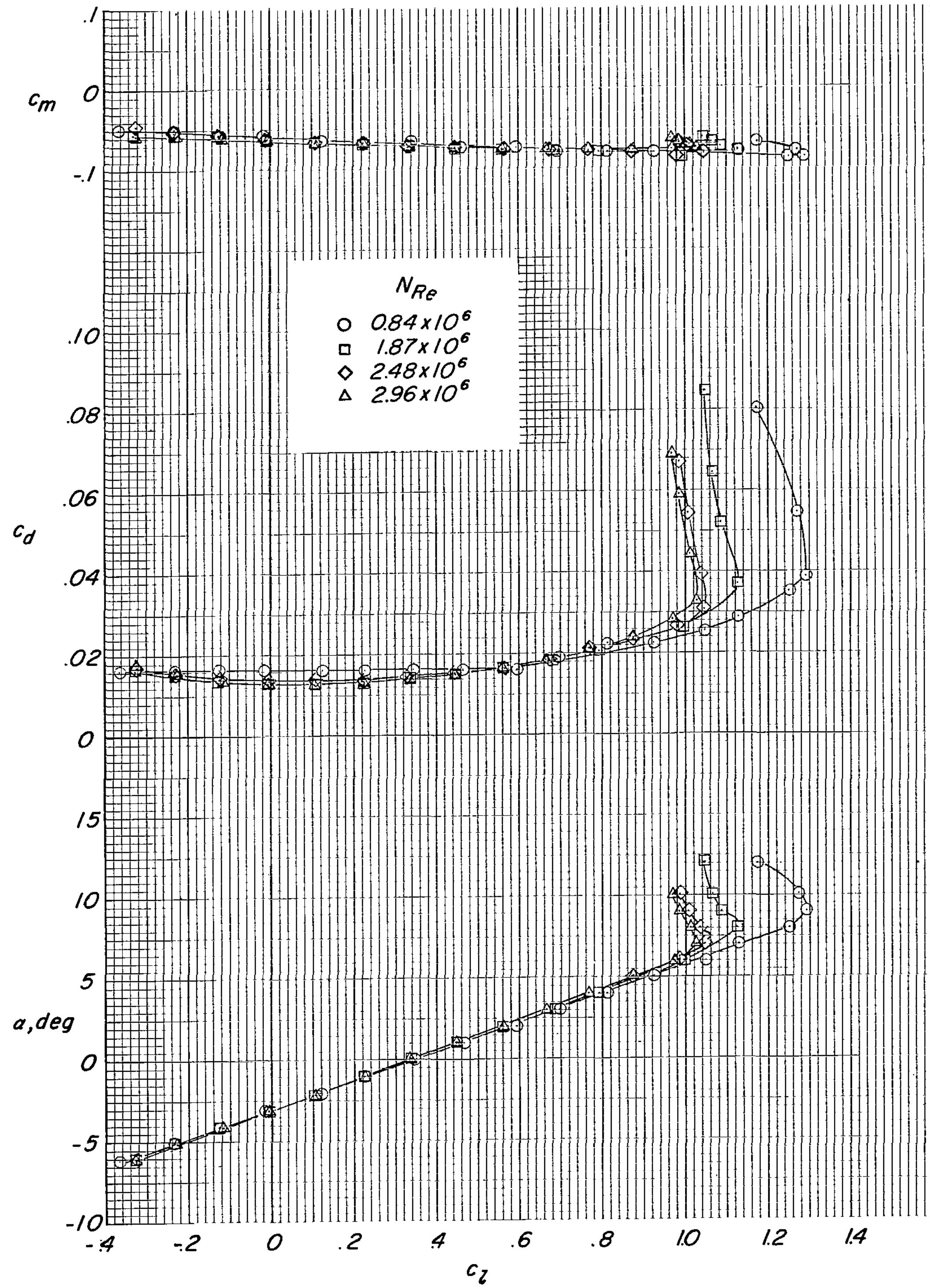


Figure 3.- Effect of Reynolds number on the section aerodynamic characteristics of the airfoil model in smooth condition.

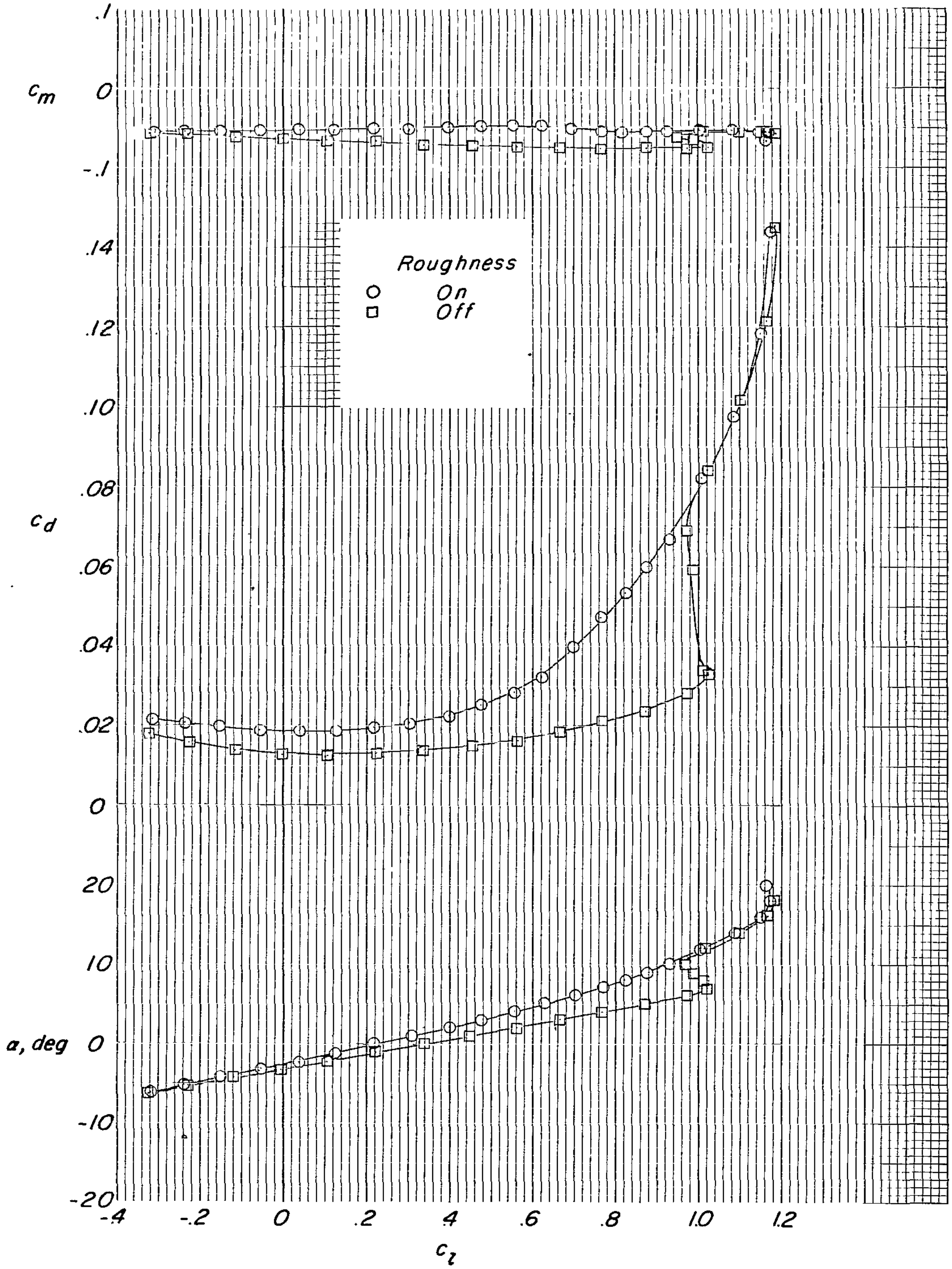


Figure 4.- Effect of roughness on the section aerodynamic characteristics of the NACA 65_5-424 airfoil. $N_{Re} = 2.96 \times 10^6$.

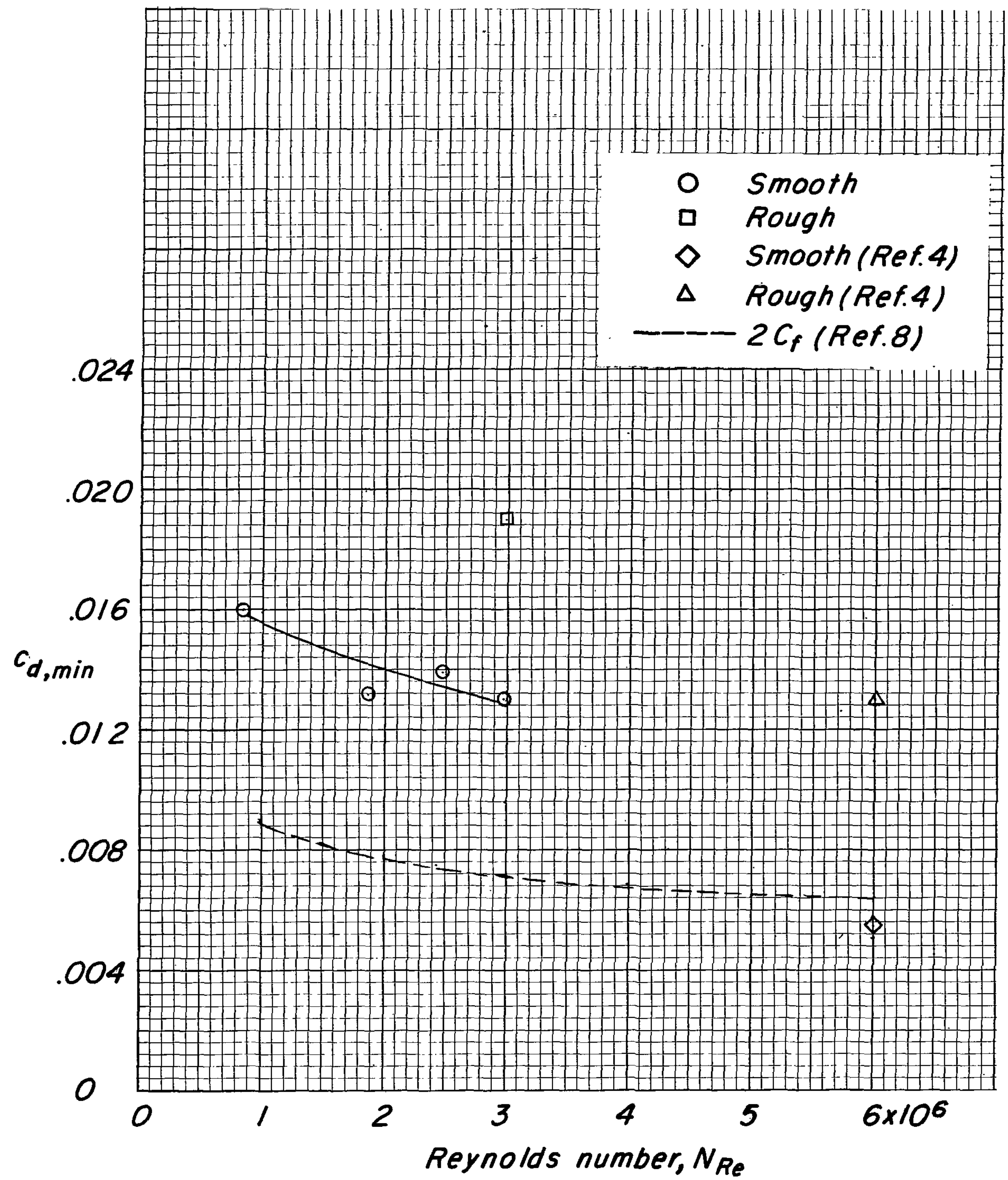


Figure 5.- Variation of minimum section drag coefficient with Reynolds number for the NACA 65_5-424 airfoil.

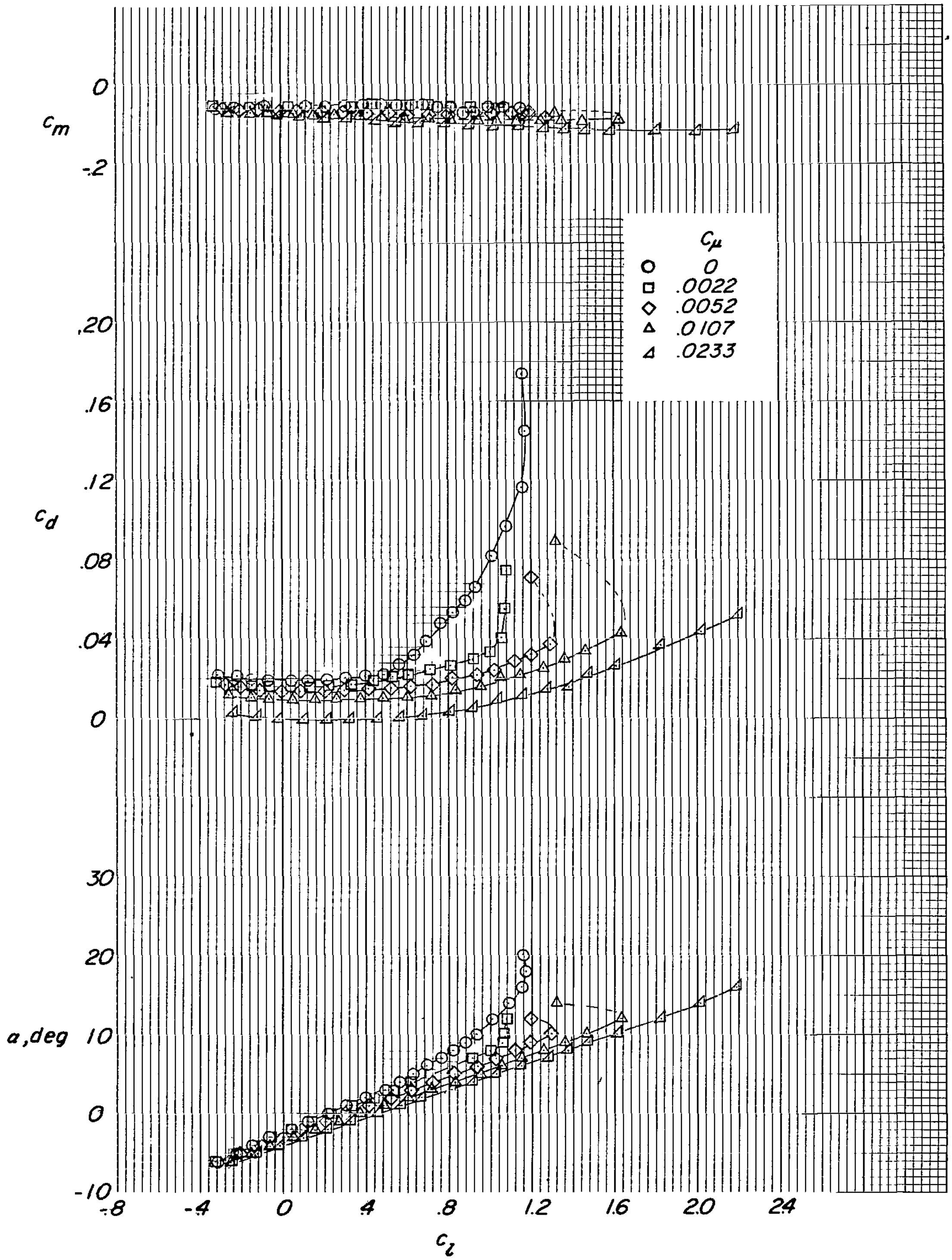


Figure 6.- Section aerodynamic characteristics of the NACA 65_5-424 airfoil. $\delta_f = 0^{\circ}$.

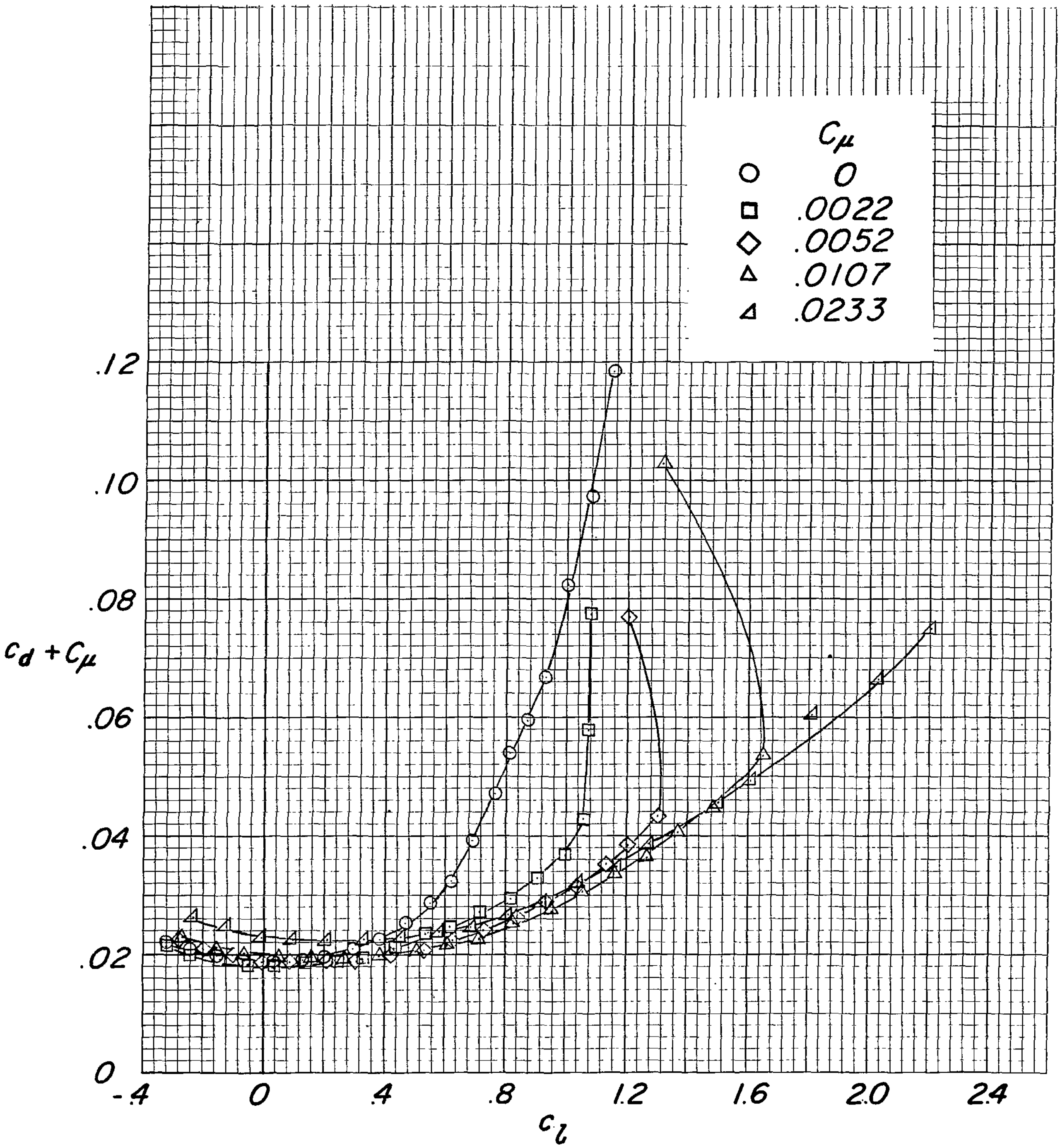
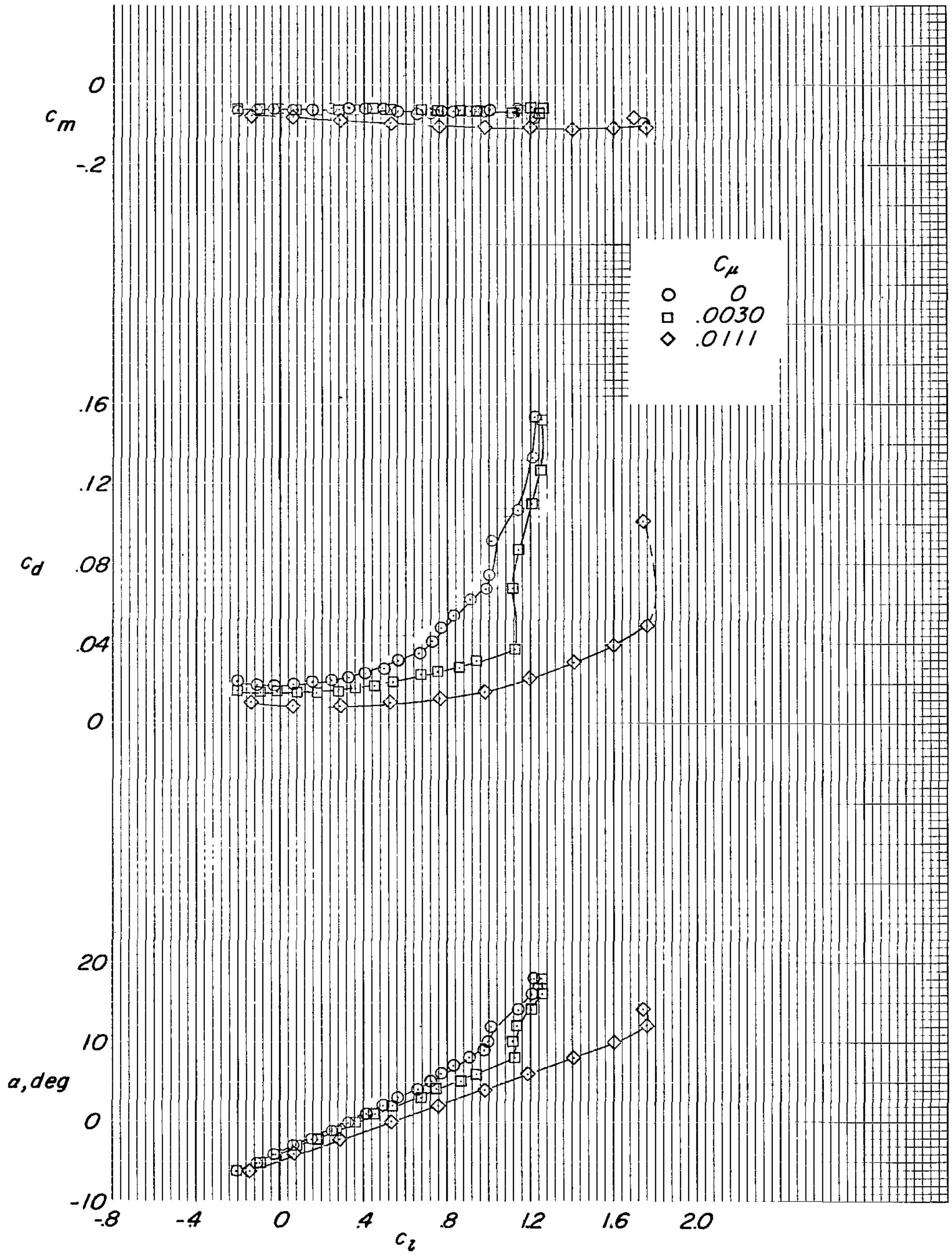
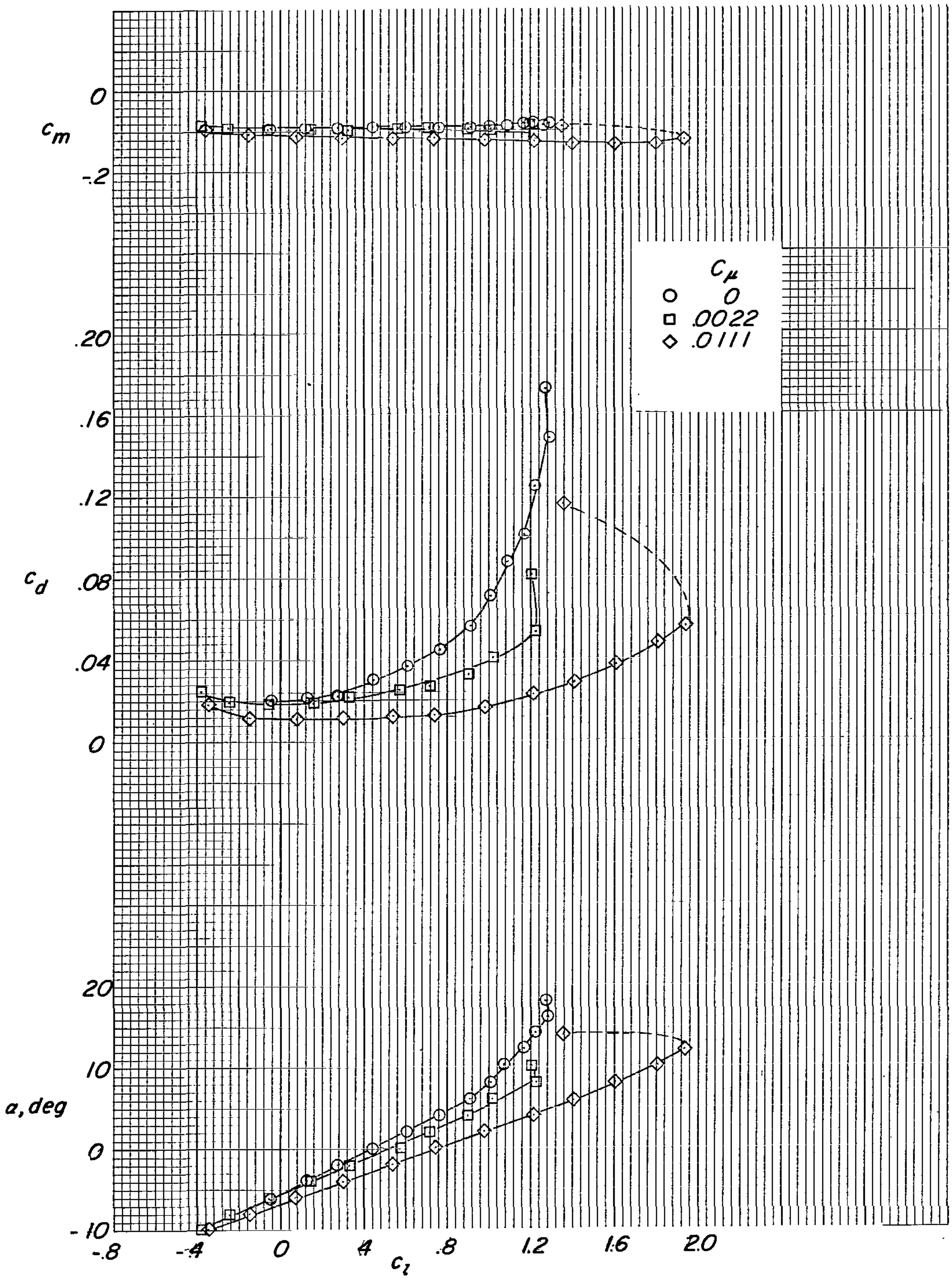


Figure 6.- Concluded.



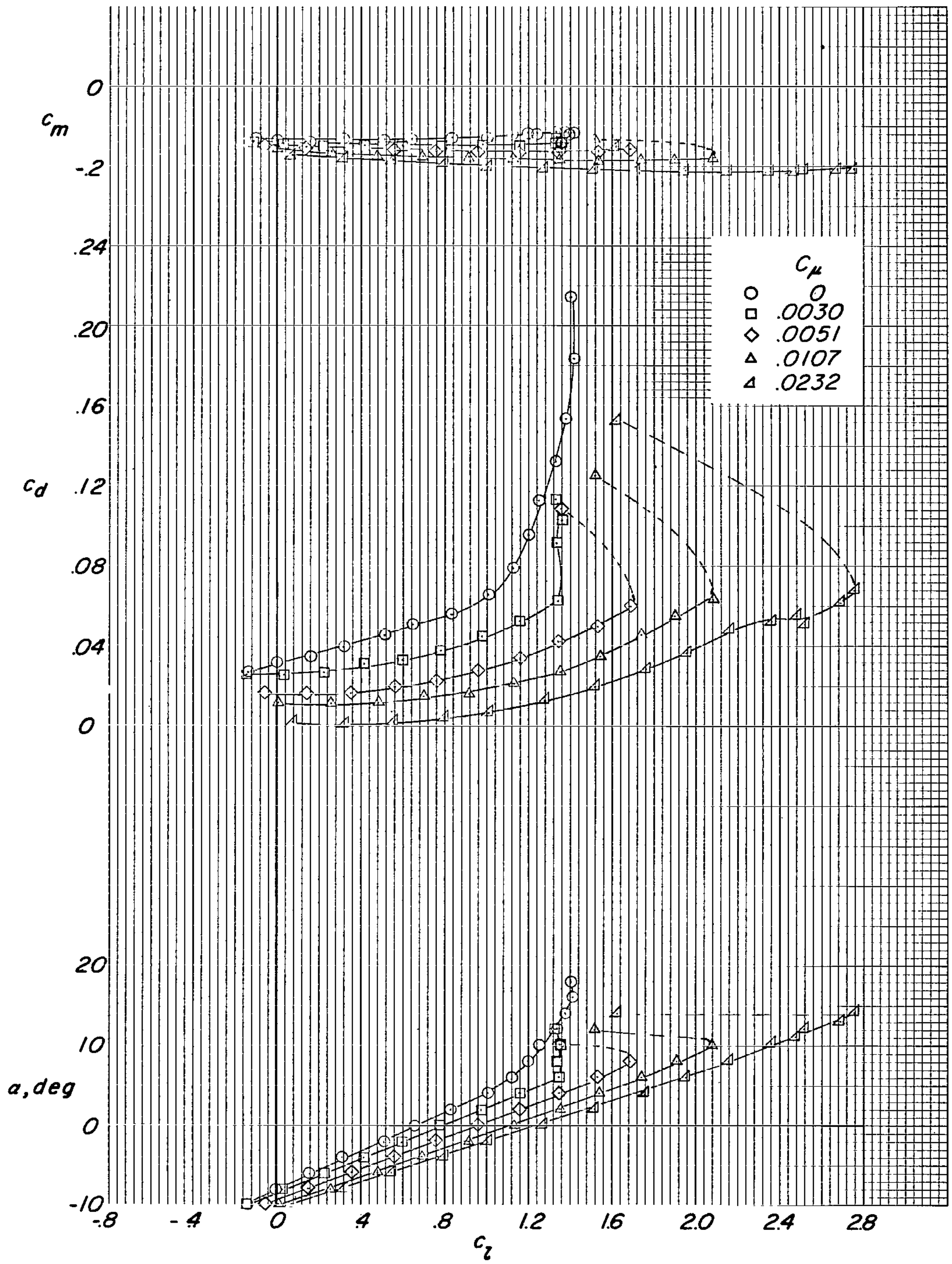
(a) $\delta_f = 2^{\circ}$.

Figure 7.- Section aerodynamic characteristics of the NACA 65_5-424 airfoil with flap deflected.



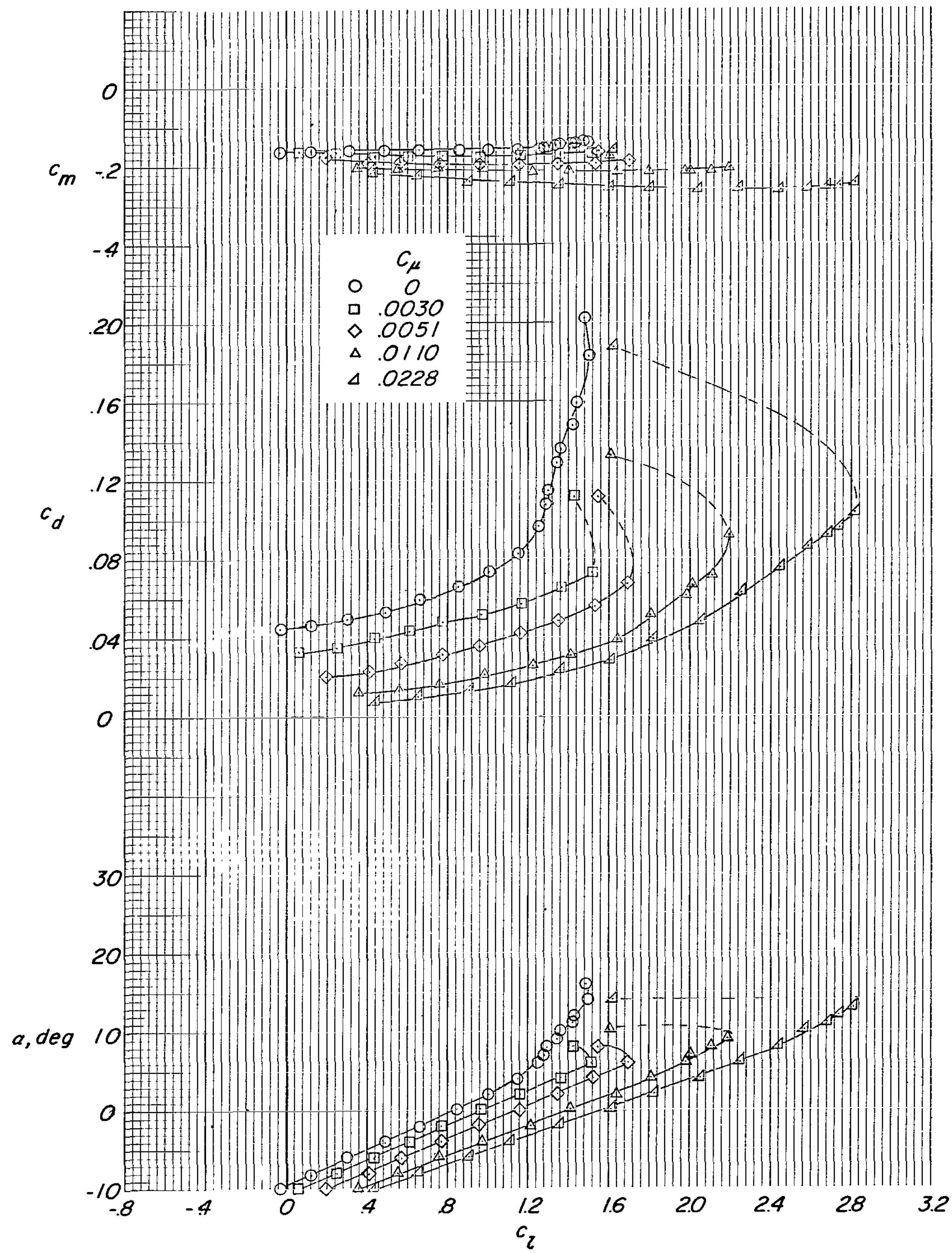
(b) $\delta_f = 5^\circ$.

Figure 7.- Continued.



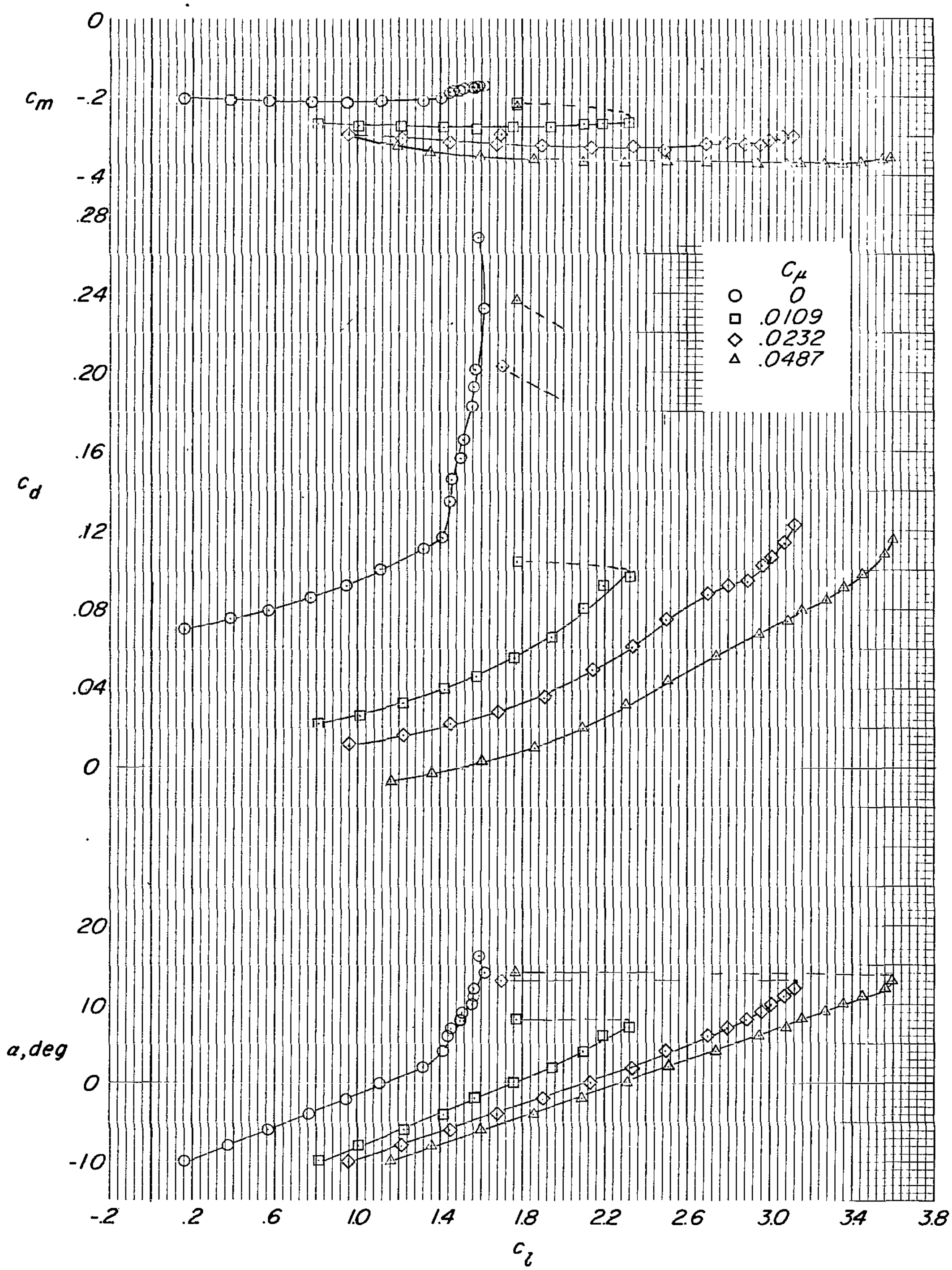
(c) $\delta_f = 10^\circ$.

Figure 7.- Continued.



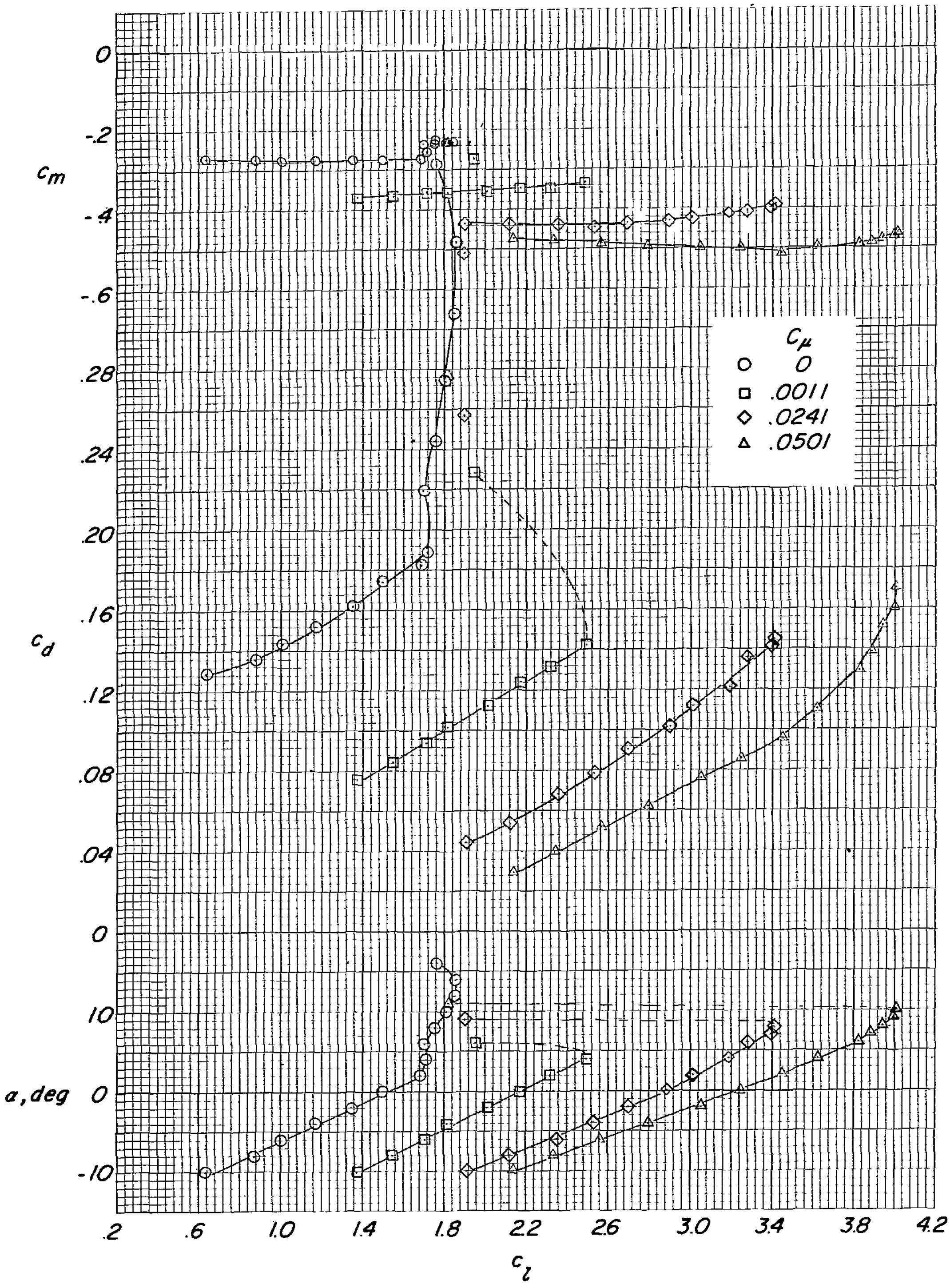
(d) $\delta_f = 15^{\circ}$.

Figure 7.- Continued.



(e) $\delta_f = 20^{\circ}$.

Figure 7.- Continued.



(f) $\delta_f = 30^{\circ}$.

Figure 7.- Concluded.

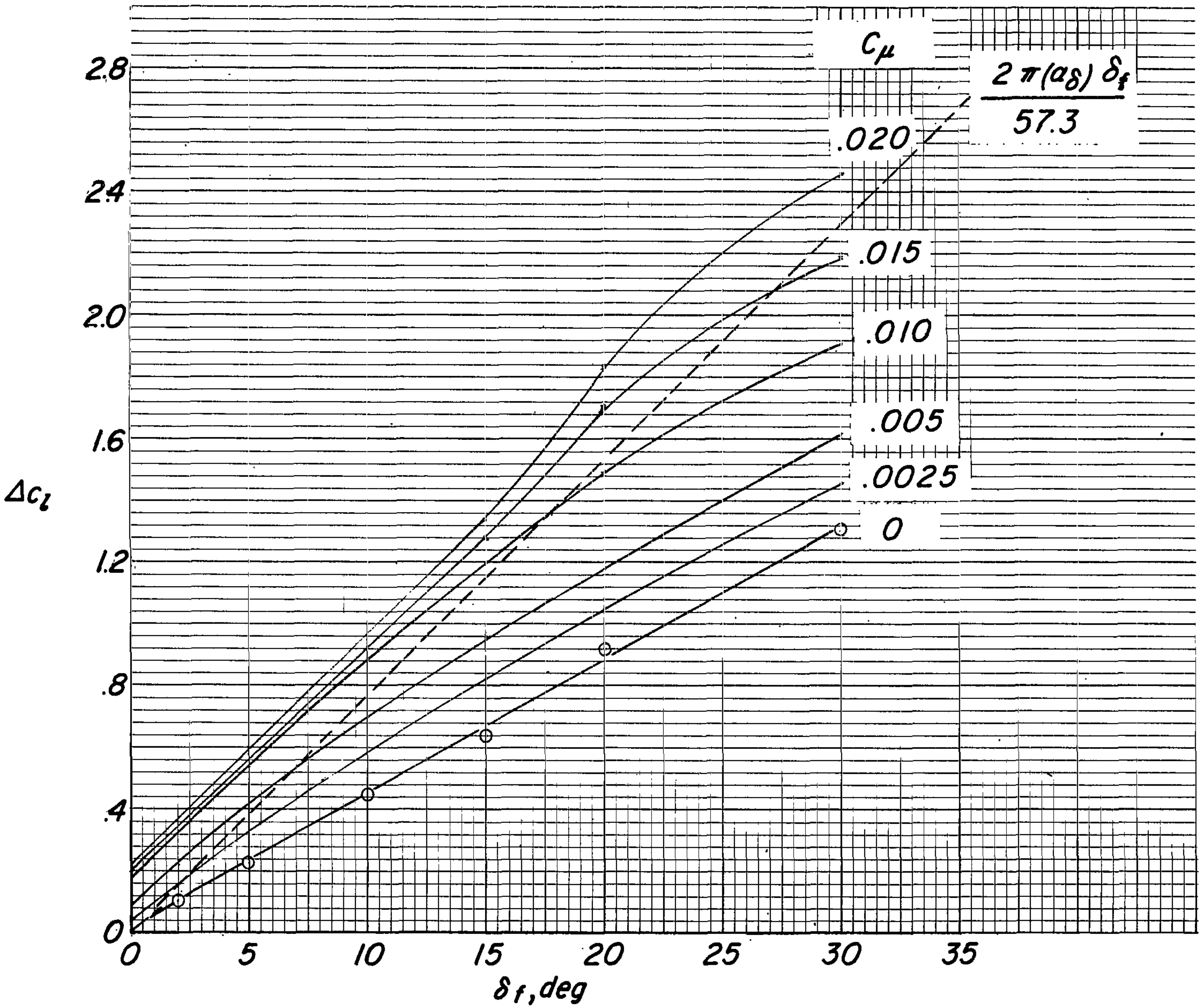


Figure 8.- Flap lift effectiveness. $\alpha = 0^{\circ}$.

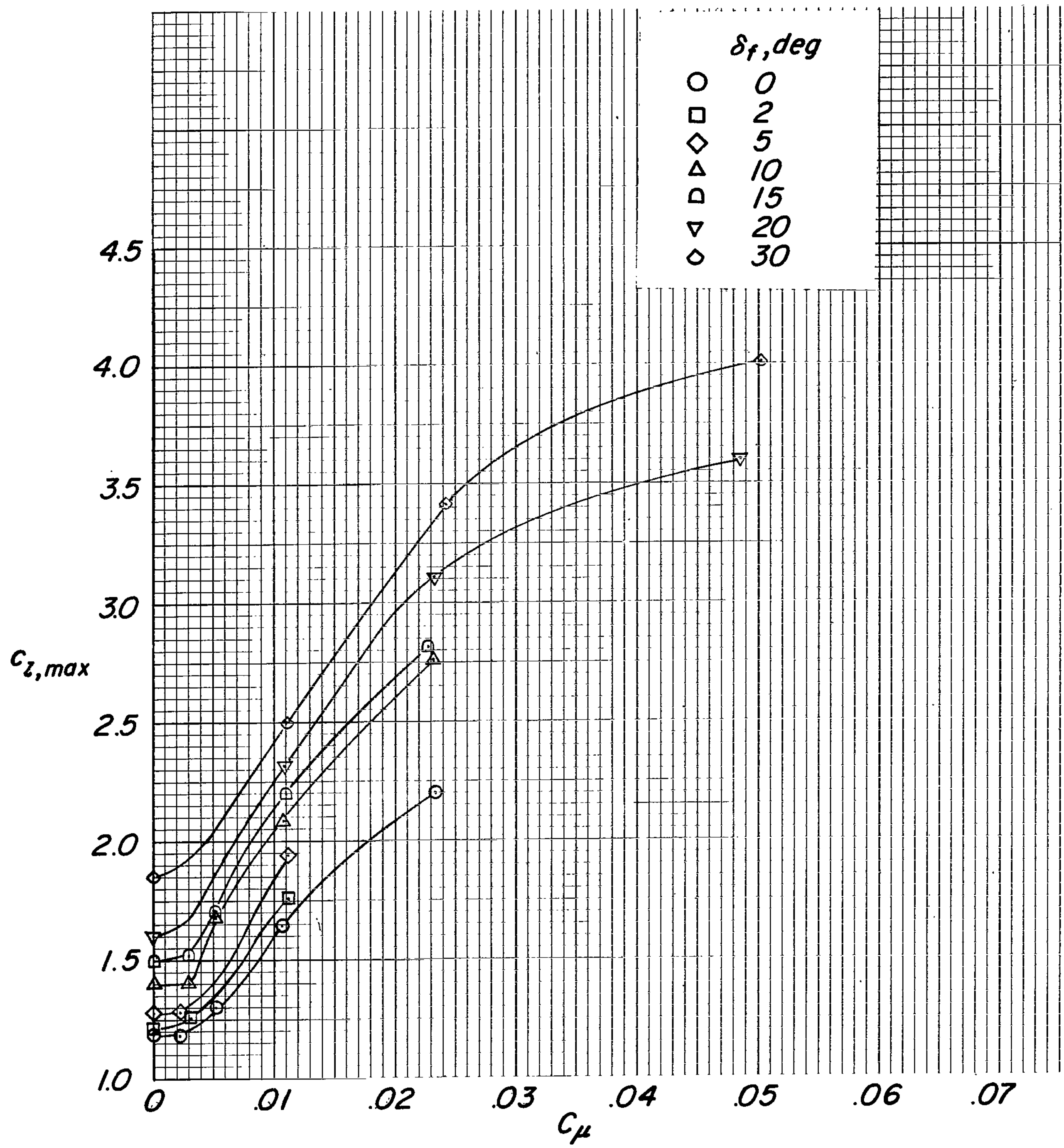


Figure 9.- Variation of maximum section lift coefficient with momentum coefficients.

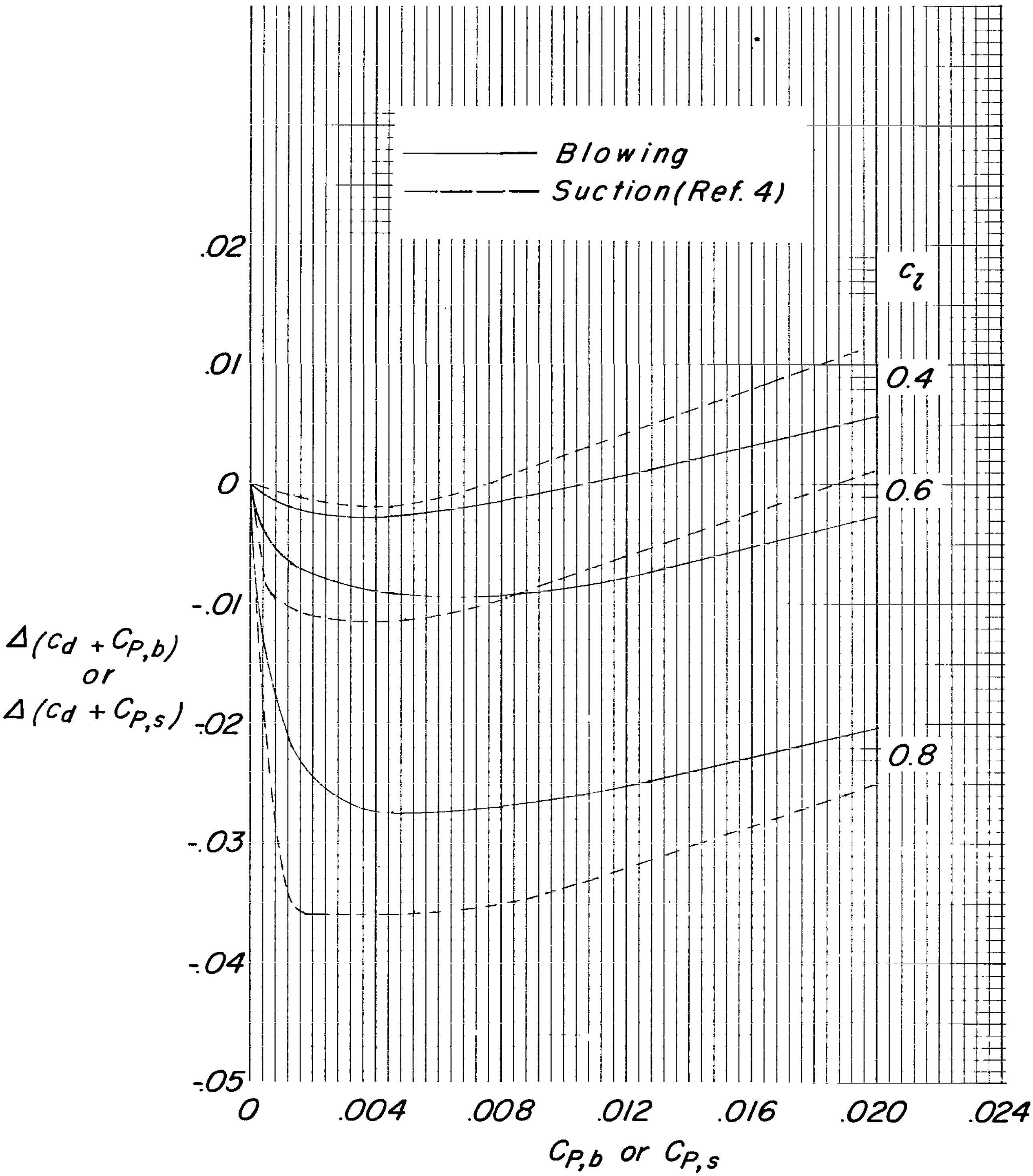


Figure 10.- Comparison of blowing and suction boundary-layer control on the airfoil section drag coefficient.

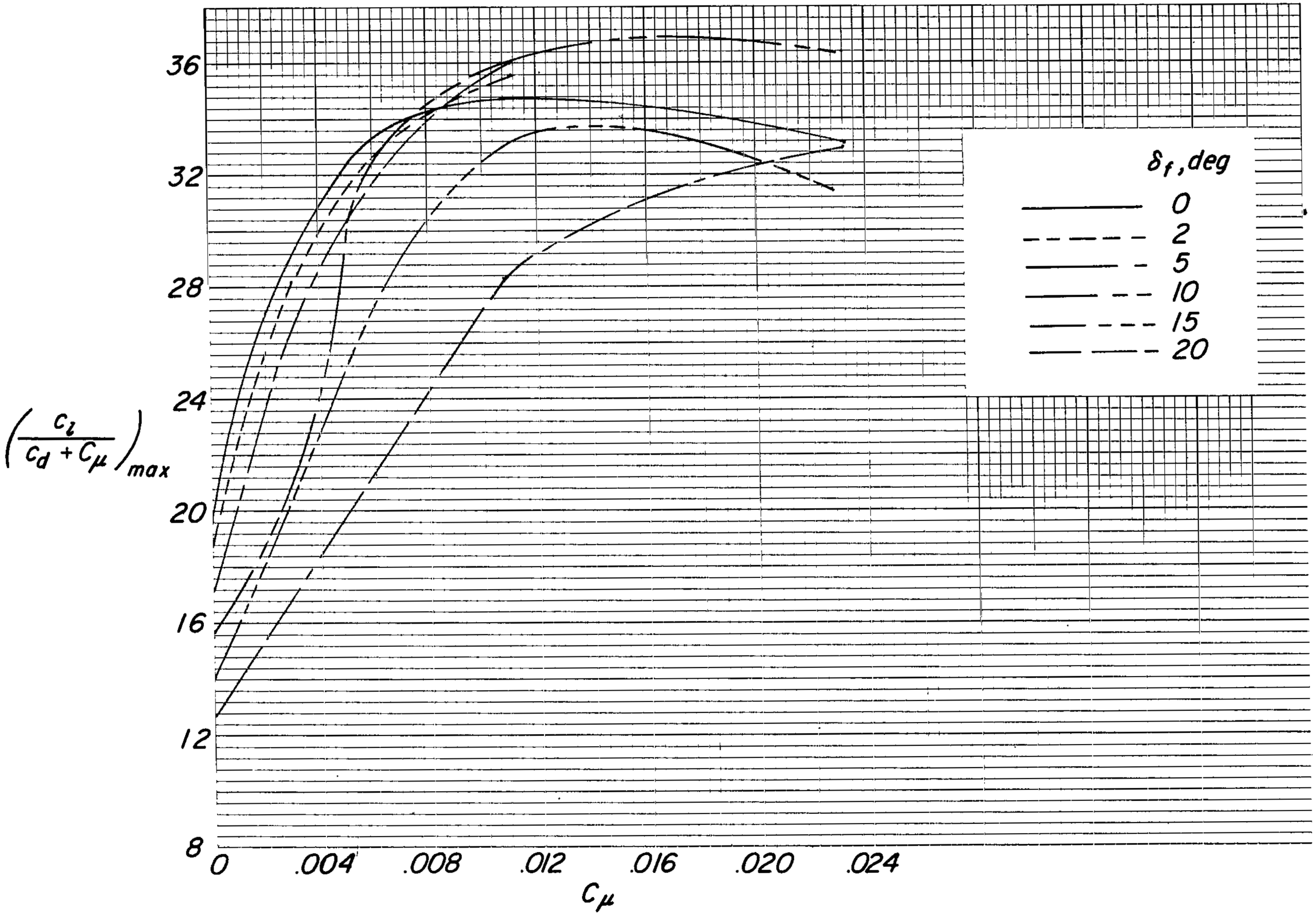


Figure 11.- Effect of momentum coefficient on the maximum lift-drag ratio of the NACA 65_5-424 airfoil.

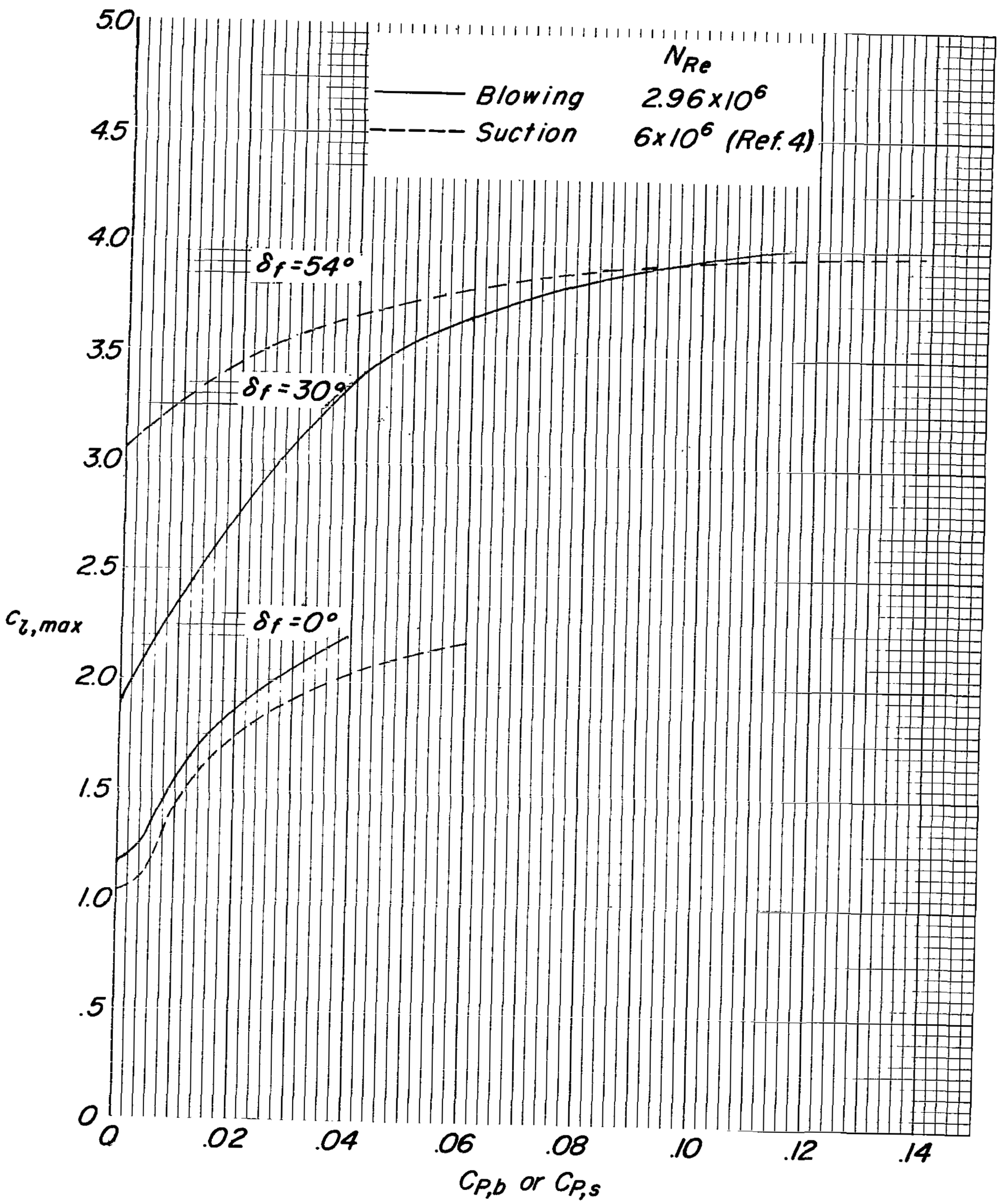


Figure 12.- Variation of maximum section lift coefficient with boundary-layer control power coefficient for blowing and suction boundary-layer control.

2/7/85

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546